CLIMATE, HYPOXIA AND FISHERIES: IMPLICATIONS OF GLOBAL CLIMATE CHANGE FOR THE GULF OF MEXICO HYPOXIC ZONE

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ABSTRACT

A large-scale hypoxic zone (< 2 mg O_2 l^{-1}) in the coastal waters of the northern Gulf of Mexico, recently approaching 20,000 km^2, overlaps with habitat and fishing grounds of commercial fish and shrimp species. Projections of general circulation models have indicated that the Mississippi River runoff would increase if atmospheric CO_2 concentration doubles. A higher freshwater runoff would be accompanied by an increase in temperatures over the Gulf Coast region of 2 to 4 °C. These two results are likely to affect water column stability, surface productivity and global oxygen cycling in the northern Gulf of Mexico, leading perhaps to an expanded hypoxic zone.

INTRODUCTION

There is a growing consensus among scientists that human activities, which have increased atmospheric concentrations of carbon dioxide (CO_2) by one-third during the last 100 years, may be responsible for an increase in global Earth's temperatures. This so-called "global warming" theory is not without challengers who argue that scientific proof is incomplete or contradictory, and that there remain many uncertainties about the nature of climate variability and climate change. Nevertheless, global temperature averages increased by almost 1 °C during the last 150 years [1], and further temperature increase seems probable. General circulation models (GCMs) forced by enhanced greenhouse gas concentrations have projected a global temperature increase of 2 to 6 °C over the next 100 years [2]. An increase in global Earth's temperature of 2 to 6 °C would likely produce an enhanced global hydrologic cycle that would be manifested in altered freshwater runoff. This hypothesis is supported by several lines of evidence, including "paleofloods", decadal trends in the freshwater runoff and GCM's scenarios.

In the United States, there is historic evidence suggesting that a change in climate enhances the frequency of extreme flood events. An analysis of a 5000-yr old geological record for the southwestern United States [3] suggested that floods occurred more frequently during transitions from cool to warm climate conditions. Apparently, modest changes in climate were able to produce large changes in the magnitude of floods. Additional evidence in support of the above hypothesis came from a 7000-yr old record of over bank floods for the upper Mississippi River tributaries [4]. Approximately 3300 years ago, an abrupt shift in flood behavior occurred, with frequent floods of a magnitude that now recurs every 500 years or more. Also, an analysis of the data collected by the U.S. Geological Survey indicated statistically significant increasing trends in monthly streamflow during the past five decades across most of the conterminous United States [5]. These results seem to support the hypothesis that enhanced greenhouse forcing produces an enhanced hydrologic cycle. One of the GCM studies [6] has examined the impact of global warming on the annual runoff of the 33 world's largest rivers. For a $2xCO_2$ climate, the runoff increases were detected in all studied rivers in high northern latitudes, with a maximum of +47 %. At low latitudes there were both increases and decreases, ranging from +96% to –43%. Importantly, the model results projected an increase in the annual runoff for 25 of the 33 studied rivers.

The northern Gulf of Mexico (Figure 1), which receives inflows of the Mississippi River - the eighth largest river in the world [7], is one of the coastal areas that may experience increased freshwater and nutrient inputs in the future. According to a GCM study referenced above [6], the annual Mississippi River runoff would increase 20% if the concentrations of atmospheric CO_2 doubles. This hydrologic change would be accompanied by an increase in summer and winter temperatures over the Gulf Coast region of 2 °C and 4 °C, respectively [8]. A higher runoff is expected during the May-August period, with an annual maximum most likely occurring in May. While there are no other GCM estimates of the Mississippi River runoff, this result is in agreement with a projected $2xCO_2$ increase in rainfall over the Mississippi River drainage basin [8].

Here we review probable implications of climate change for the Gulf of Mexico hypoxic zone, focusing on two areas: (1) coupling between climate variability, freshwater runoff of the Mississippi River, and hypoxia in the coastal northern Gulf of Mexico, and, (2) potential implications of global climate change for coastal fisheries in the hypoxic zone. In this analysis we use our previously published physical-

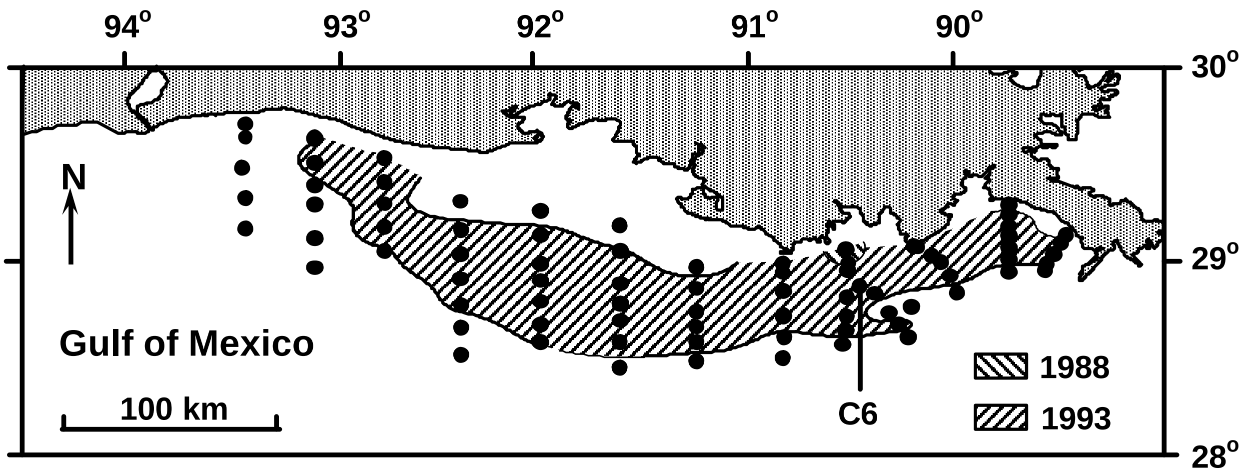

FIGURE 1. Map of the northern Gulf of Mexico showing station grid and location of station C6. Shaded areas represent the distribution of hypoxic (< 2 mg O_2 l^{-1}) bottom waters during August 1988 and July 1993.

biological model [9] [10] and extensive long-term data sets collected at station within the core of the Gulf of Mexico hypoxic zone (C6, Figure 1).

COUPLING BETWEEN CLIMATE AND HYPOXIA

Climate change, if manifested by increasing riverine freshwater inflow, may affect coastal and estuarine ecosystems in several ways. First, changes in freshwater inflow will affect the stability of the water column, and this effect may be enhanced due to changes in sea surface temperatures. Vertical density gradients are likely to increase, that could decrease vertical oxygen transport and create conditions in the bottom water favorable for the development of severe hypoxia or anoxia [9]. Second, the concentrations of nitrogen (N), phosphorus (P), and silicon (Si) in riverine freshwater inflows are typically an order of magnitude higher than those in coastal waters [11]. The mass fluxes of riverine nutrients are generally well-correlated with integrated runoff values [12] [13]. Consequently, the nutrient inputs to the coastal ocean are expected to increase as a result of the increasing riverine runoff, which could have an immediate effect on the productivity of coastal phytoplankton. Third, the stoichiometric ratios of riverine nutrients, Si:N, N:P and Si:P, may differ from those in the coastal ocean [11]. Increased freshwater inflow, therefore, may also affect coastal phytoplankton communities by increasing or decreasing a potential for single nutrient limitation and overall nutrient balance [11] [14] [15]. Thus, it appears that there is a plausible link between global climate change and the productivity of river-dominated coastal waters.

Changes in the areal extent of hypoxic (< 2 mg O_2 l^{-1}) bottom waters provide a representative example of the riverine influence on coastal productivity processes (Figure 1). The northern Gulf of Mexico is presently the site of the largest (up to 20,000 km^2) and most severe hypoxic zone in the western Atlantic Ocean [16] [17]. Hypoxia normally occurs from March through October in waters below the pycnocline, and extends between 5 and 60 km offshore [16]. During the drought of 1988 (a 52-year low discharge record of the Mississippi River), however, bottom oxygen concentrations were significantly higher than normal, and formation of a continuous hypoxic zone along the coast did not occur in midsummer (Figure 1). The opposite occurred during the Great Flood of 1993 (a 62-year maximum discharge for August and September), when the areal extent of summertime hypoxia doubled with respect to the average hydrologic year [17]. Hypoxia in the coastal bottom waters of the northern Gulf of Mexico develops as a synergistic product of high surface primary productivity, which is also manifested in a high carbon flux to the sediments, and high stability of the water column [19]. Likewise, the 1993 event was associated with both an increased stability of the water column and nutrient-enhanced primary productivity, as indicated by the greatly increased nutrient concentrations and phytoplankton biomass in the coastal waters influenced by the Mississippi River [17] [19].

MODEL SCENARIOS FOR THE NORTHERN GULF OF MEXICO

In a series of modeling studies [9] [10], we used a coupled physical-biological model with climate forcing to examine the impacts of climate variability on the Gulf of Mexico hypoxic zone. Model simulations suggested that increased riverine freshwater runoff (20%) and increased temperatures (2-4 ^{o}C) would significantly affect the stability of the water column. Vertical density gradients between the upper (0-10 m) and the lower (10-20 m) water column would increase, and would likely exceed values observed during the peak of the Great flood of 1993 [9]. Increased riverine nitrogen flux during the late spring would enhance the net productivity (NP) of the upper water column. Following a 20% increase in the annual Mississippi River runoff, the annual NP value at a station within the core of the hypoxic zone would increase 53%, from 122 gC m^{-2} yr^{-1} (1985-1992) to 187 gC m^{-2} yr^{-1}. This later value is 21% higher than the annual NP value for the Great Flood of 1993. Model results also suggested that summertime subpycnoclinal (10-20 m) oxygen content would decrease 30-60%, relative to the 1985-1992 average. This would cause almost total oxygen depletion in the lower water column, which may persist for several weeks (Figure 2). It is unlikely, however, that increased carbon deposition would further enhance benthic and epibenthic respiration within the present day hypoxic zone, since bottom waters are already severely depleted in oxygen. More likely, a significant portion of the sedimented organic matter resulting from increased production will be buried or, perhaps, exported from the area, leading to an expanded hypoxic zone.

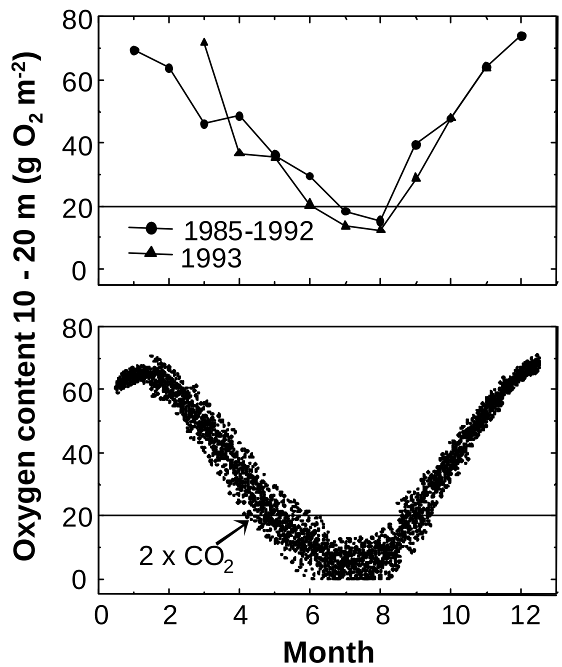

FIGURE 2. Seasonal changes in the integrated subpycnoclinal oxygen content (10-20m) at station C6 in the core of the hypoxic zone. Observed monthly averages for 1985-1992 and 1993 are compared to a Monte-Carlo simulation for a 2xCO_2 climate. The 2xCO_2 probability plot is comprised of 2880 points.

IMPLICATIONS FOR COASTAL FISHERIES

Freshwater runoff, via its negative effect on salinity, is a critical parameter governing biological processes in the northern Gulf of Mexico estuaries and coastal waters. The annual yield of penaeid shrimp in the Gulf of Mexico is inversely related to the annual discharge of the Mississippi River, perhaps because of reduced estuarine salinities at high river flows [20] [21]. Penaeid shrimp postlarvae are mostly limited to estuarine habitats with salinities greater than 10 psu. In the case of Louisiana, salinities are primarily influenced by river flow and precipitation. Mississippi River discharge affects the lower estuaries, while rainfall affects the upper bays and estuaries. With heavy rains or high river flow, salinities in the marshes are reduced. If salinities are reduced beyond acceptable conditions, postlarvae do not move as high into the marshes, ultimately influencing adult stock. This is important because if the freshwater runoff increases as a result of global warming, estuarine salinities may decrease, possibly leading to reduced yields of shrimp and other species favoring higher estuarine salinities. Temperature also influences growth. Growth is inhibited in waters with a temperature below 20 ^{o}C. Global warming may expand this region of high shrimp yield northwards, increasing shrimp harvest throughout the region, assuming that salt marsh nursery areas are not negatively affected by other factors, such as water level changes.

The effects of hypoxia on demersal and benthic communities will likely intensify as hypoxia stress worsens, due to either increase in areal extent, severity, or duration. Catches in trawls are negligible when the bottom dissolved oxygen concentration falls below 2 mg l^{-1} [22] [23]. Motile fishes and invertebrates migrate from the area or into the upper water column. Mass mortalities are likely, however, if they are trapped against the shore by a large anoxic water mass. This could become a serious problem in the northern Gulf of Mexico, if the areal extent of hypoxia increases. Heavy mortalities occur in the benthic infauna and species diversity is drastically reduced when ambient oxygen concentrations decrease below 0.5 mg l^{-1} [24] [25] 26]. Presently, there is some recovery of the benthic community in the fall, and further recruitment in the subsequent spring. However, the overall structure of the benthic community is shifted in species composition and age structure, to a smaller-sized, lower biomass, polychaete dominated fauna. An increase in areal extent and severity of hypoxia will decrease recovery rates and also reduce food resources (infauna) for recolonizing demersal groups, such as the commercially important penaeid shrimps. Further, alterations in benthic community structure will have implications for sedimentary processes, benthic pelagic coupling, and energy flow. Major alterations in benthic communities due to hypoxia stress, especially a reduction in diversity and biomass, will certainly alter the productivity base that leads to fishery stocks.

Louisiana commercial and recreational fisheries depend on life cycles of species located within shallow continental shelf waters that overlap with the hypoxic zone. Fishery-independent surveys reveal reduction or absence of shrimp in hypoxic waters [27]. Both abundance and biomass of fishes and shrimp are significantly reduced where oxygen concentrations in bottom water fall below 2 mg l^{-1} [23]. Under experimental conditions, white shrimp avoid water with dissolved oxygen concentrations below 1.5 mg l^{-1} and brown shrimp are even more sensitive, avoiding water with oxygen concentrations below 2.0 mg l^{-1} [28]. The ability to detect and avoid hypoxic water leads to an observed blocking effect on juvenile shrimp emigrating from inshore nurseries to offshore feeding and spawning grounds. The life cycle of shrimp involves offshore (Gulf shelf) and inshore (estuarine) phases. Adults spawn on the Louisiana and Texas shelf. Resulting larvae immigrate as plankton via currents into coastal estuaries. Within the estuaries, postlarvae metamorphose into small juvenile shrimp that are benthic in habit. After about two months, intermediate size juveniles emigrate from the nursery and return to the outer shelf to complete their growth into adults. The life cycle from egg to adult takes about 6 months. Larval, postlarval, sub-adult and adult shrimp utilize habitats overlapping with the hypoxic zone, and, depending on the stage within the life cycle, their spawning grounds, feeding grounds or migratory pathways may be impacted. A negative correlation between shrimp catch and the presence of hypoxia corroborates interference with shrimp migration [29] [30]. In areas where hypoxia is widespread and persistent, shrimp catch is always low. In Louisiana, the nearshore concentration of shrimp is always higher than offshore, possibly because hypoxia impedes offshore movement. Since nearshore catches are comprised of young shrimp, productivity in growth to a larger size is lost. Production models conservatively estimate that several million pounds of shrimp are lost annually due to early harvest. Since hypoxia blocks access of migrating juvenile shrimp to offshore feeding grounds, losses in production due to lost feeding are also predictably large.

Pelagic fishes may also be impacted if hypoxic conditions extend high into the water column affecting their distribution and movement patterns. From August 1995 to February 1997, for example, dual beam hydroacoustics were employed on quarterly research trips to measure the density and *in situ* target strengths of fishes associated with a petroleum platform, South Timbalier 54 [31]. During the survey in July 1996, observed dissolved oxygen levels were below 2 mg O_2 l^{-1} in depths of 15-22 m. Within these depths fish density was essentially zero while from the surface to 15 m elevated fish densities were observed. Other potential fisheries impacts include: concentrated fishing effort with increased bycatch, local nearshore mortality of finfish and shellfish related to the “jubilee” phenomenon, and decreased recruitment due to impacts on zooplankton assemblages [32]. These direct and indirect fisheries losses would be exacerbated if hypoxia expands in space and time as a result of global climate change.

CONCLUSIONS

Projections of general circulation models suggest that freshwater discharge from the Mississippi River to the coastal ocean would increase 20% if atmospheric CO_2 concentration doubles. A higher Mississippi River runoff would be accompanied by an increase in winter and summer temperatures over the Gulf Coast region of 4.2 ^oC and 2.2 ^oC, respectively. This is likely to affect the global oxygen cycling of the northern Gulf of Mexico, which is presently the site of the largest (up to 20,000 km^2) and the most severe coastal hypoxic zone (<2 mg O_2 l^{-1}) in the western Atlantic Ocean. Model simulations suggest a close coupling between climate variability and hypoxia, and indicate a potential for future expansion of the Gulf’s hypoxic zone as a result of global warming. In simulation experiments, a 20% increase in annual runoff of the Mississippi River, relative to a 1985-1992 average, resulted in a 50% increase in net primary productivity of the upper water column (0-10 m) and a 30-60% decrease in summertime subpycnoclinal (10-20 m) oxygen content within the present day hypoxic zone. Those model projections are in agreement with the observed increase in severity and areal extent of hypoxia during the flood of 1993. Because of large uncertainties in the climate system itself, and also at different levels of biological control, it is difficult to predict how climate change may affect coastal food webs. Nevertheless, future expansion of the coastal hypoxic zones would have important implications for habitat functionality and sustainability of coastal fisheries.

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